HIGH HOT-HARDNESS GEAR/ LUBRICANT EVALUATIONS

INTERIM REPORT
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By

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A WADD gear machine was used to evaluate the gear load-carrying capacities of three high-hot-hardness gear materials, Cartech EX 00014, CBS 1000 M, and Vasco X-2 ESR, at 74°C and 218°C (165°F and 425°F). One MIL-L-23699C lubricant was used to evaluate all three gear materials at the two test temperature levels. Three additional military specification type turbine engine lubricants were included in the evaluation

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20. ABSTRACT (Cont'd)

of the Vasco X-2 ESR gear material. An increase in gear load-carrying capacity, ranging from 10 to 35 percent, was obtained for the three high-hot-hardness gear materials when compared with equivalent 74°C (165°F) data using AMS 6260 steel gears. A candidate MIL-L-27502 lubricant provided the highest load-carrying capacity at 74°C (165°F) test conditions using the Vasco X-2 ESR test gears. It is shown that the load-carrying capacity of gears made from different materials do not necessarily have the same relative ranking when evaluated at two different temperature levels.

FOREWORD

This document is the final report of a program conducted at the U.S. Army Fuels and Lubricants Research Laboratory (AFLRL) at Southwest Research Institute, San Antonio, Texas, under Contracts DAAK70-78-C-0001 and DAAK70-80-C-0001, during the period January 1978 through September 1980. The contract monitor was Mr. F. W. Schaekel of the Energy and Water Resources Laboratory, U.S. Army Mobility Equipment Research and Development Command (MERADCOM), DRDME-GL, Ft. Belvoir, VA.

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I. INTRODUCTION

In conjunction with a technical program interchange, the U.S. Army Applied Technology Laboratory (USAATL) requested MERADCOM assistance to develop an improved turbine engine oil having increased gear load-carrying capacity with the capability of operating at higher temperatures. In addition, the developed oil should not sacrifice the acceptable performance characteristics of the current MIL-L-7808 and MIL-L-23699 turbine engine lubricants. This effort was aimed toward supporting the Army's future needs in the areas of newly-designed helicopter turbine engines and advanced transmissions and for possible applications in the new AGT 1500 turbine engine scheduled for use in the Army's new XM-1 tank.

Initial emphasis was placed on comparing the requirements of four aircraft turbine engine oils. The requirements for the most current military specification for MIL-L-7808(1)*, MIL-L-23699(2), MIL-L-27502(3), and XAS-2354(4) were summarized and studied. Lubrication personnel from MERADCOM and AFLRL met at the Air Force Aero Propulsion Laboratory (AFAPL) and Naval Air Propulsion Center (NAPC) to discuss Army needs and to discuss the state-of-the-art of turbine engine oils. An in-depth trip report(5) concerning these meetings was prepared and submitted to MERADCOM in February 1978. In general, it is the opinions of both the Air Force and Navy lubrication specialists that the most recent lubricants added to the Qualified Products List, for both the MIL-L-7808H and MIL-L-23699C specifications, represent the current state-of-the-art for turbine engine lubricants. The Air Force does not have a qualified product as yet for the MIL-L-27502 lubricant specification, but work is continuing in evaluating candidate oils as they become available to the Air Force. While the Navy is interested in higher gear load characteristics, as included in its experimental development lubricant specification XAS-2354, little future effort is planned in this area. Most of the current and near future Navy effort will be directed towards the development of a corrosion-resistant MIL-L-23699 turbine engine oil.

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*Superscript numbers in parentheses refer to the List of References at the end of this report.

USAATL personnel have indicated that manufacturers of Army helicopter systems are concentrating on selected high-hot-hardness gear materials for use in advanced helicopter gearbox applications. The majority of the current helicopter gearboxes use AMS-6260 gear material, which is not effective for operation at temperatures above 150° to 175°C (302° to 347°F) due to a loss in hardness when subjected to temperatures above this range. Earlier work performed at Southwest Research Institute (SwRI) under Air Force sponsorship has shown that the type of gear material used is of extreme importance in evaluating gear lubricants.[6] Based on this information and other available research[7,8], a modest gear test program using special high-temperature test gears made from Vasco X-2 ESR (Electro Slag Remelt) material furnished by the Army Materials and Mechanics Research Center (AMMRC), and four turbine engine lubricants (one MIL-L-7808H, one MIL-L-23699C, one corrosion-inhibited MIL-L-23699 candidate, and one MIL-L-27502 candidate) was conducted at two temperature conditions, 74°C and 218°C (165°F and 425°F). In addition, the NAPC provided special high-temperature test gears made from Cartech EX 00014 and CBS 1000 M, which were included in the gear program. Due to the very limited number of Cartech EX 00014 and CBS 1000 M test gears available, they were evaluated only at the 218°C (425°F) test temperature conditions using the MIL-L-23699C lubricant.

It should be noted that the NAPC evaluated the Cartech EX 00014 and CBS 1000 M test gears earlier in a WADD gear machine at the 74°C (165°F) test temperature condition using the MIL-L-23699C lubricant. The results from these NAPC tests are reported in Reference 8, and are included in a later section of this report in order to obtain the maximum amount of comparative data while keeping costs to a minimum.

II. TEST EQUIPMENT AND PROCEDURES

A. WADD Gear Machine

A WADD gear machine was employed in this gear load-carrying capacity investigation. The design features of the machine are described in detail in ASTM Test Method D 1947, Standard Test Method for Load-Carrying Capacity of Petroleum Oil and Synthetic Fluid Gear Lubricants. Its four-square operating principle and critical dimensions are identical to those of the older and more widely used Ryder gear machine.[9] The major differences lie in the materials of construction and certain design details, which permit the WADD gear machine to operate at significantly higher test gear temperatures and speeds than the Ryder gear machine.

Briefly, the WADD gear machine differs from the Ryder gear machine in that each shaft is supported by two double-row roller bearings instead of three journal bearings. It has one load chamber located on the end of the driven shaft, rather than two load chambers located in the middle portion of both shafts. Screw-thread type nonrubbing seals, rather than elastomer seals, are used to separate the test oil and support oil chambers; and the case is made of tool-steel to improve structural stability at elevated temperatures.

Two replaceable spur gears are used in both the WADD and the Ryder gear machines as the test gears. The test gears are mounted on two shafts having integral, matching helical slave gears. The test gear tooth load is derived from the application of a controlled hydraulic oil pressure to the load system. This hydraulic load causes a slight axial movement between the two shafts, which in turn produces a normal tooth load on the test gears by virtue of the helical slave gears. The test gear tooth load is computed from the applied hydraulic load and the geometry of the load system. Extensive calibrations of the WADD machine[6] have shown that the computed tooth load is valid for speeds up to 20,000 rpm, test oil temperature up to 205°C (401°F), and test gear temperatures up to 370°C (698°F).

An Erdco universal drive system is used to drive the WADD gear machine. This drive system consists of a 50-hp induction motor which drives the machine through a variable speed coupling, a step-up gearbox, and an adaptor block to which the machine is attached. The test gear speed is controlled at 10,000 rpm by adjusting the field excitation of the variable speed coupling.

B. Test Oil System

A test-oil system capable of maintaining test-oil temperatures up to 205°C (401°F) is used with the WADD gear machine. The capacity of the test-oil system is 1 liter. Test oil is supplied to the test gears at 270 mℓ/min. by means of a pressure pump through an inline filter and then to the jet, located on the unmeshing side of the gears. The oil is gravity drained from the test section through a flow check chamber and returned to the sump. Oil temperature to the test gears is maintained constant by means of two electrical band heaters located on the outside of the test-oil sump.

C. Test Gears

Three different high-hot-hardness gear materials, Cartech EX 00014, CBS 1000 M, and Vasco X-2 ESR, were evaluated in this investigation. The elemental analyses of the three gear materials are presented in Table 1 along with the nominal composition of AMS 6260 steel, the material used in the manufacture of standard Ryder test gears. The test gears used were all special spur gears having 28 teeth, 8.89 cm (3.5 in.) pitch diameter, 8 dimetral pitch, and a 22.5 degree pressure angle.

The dimensions of the test gears used in high-temperature gear tests are essentially the same as those used in the standard 74°C (165°F) test; however, it is necessary to reduce the width of the gear teeth on the wide

TABLE 1. ELEMENTAL ANALYSES OF FOUR GEAR MATERIALS

Elemental Analysis,[a] Percent by Weight	AMS 6260[b]	Cartech EX 00014[b]	CBS 1000 M[b]	Vasco X-2 ESR
Carbon	0.1	0.12	0.14	0.14
Manganese	0.55	0.20	0.50	0.27
Silicon	0.25	1.00	0.50	0.81
Phosphorus	0.025	0.025	0.025	0.012
Sulfur	0.025	0.025	0.025	0.011
Chromium	1.25	1.00	1.05	5.04
Molybdenum	0.12	0.75	5.00	1.34
Nickel	3.25	3.00	3.00	--
Vanadium	--	0.10	0.325	0.44
Copper	--	2.00	--	--
Tungsten	--	--	--	1.38

(a) Balance Iron.

(b) Data from Reference 8.

gear to approximately 0.952 cm (0.375 in.) rather than 2.381 cm (0.9375 in.) in order to accommodate the induction heating coil required to heat both the narrow and wide test gears for the 218°C tests. This reduction in tooth width has little, if any, effect on the test results since the reduced width still allows ample contact area for the 0.635 cm (0.25 in.) wide teeth of the narrow test gear during test.

The Cartech EX 00014 and CBS 1000 M wide test gears supplied by the NAPC were machined to provide the 0.952 cm (0.375 in.) tooth width prior to being evaluated.

The web of each side of each narrow test gear was electroplated with black chromium in order to facilitate the accurate measurement of gear temperature during test.

D. Test Procedures

Two basic test procedures were used with the WADD gear machine. One procedure, described in detail by ASTM Method D-1947, was used to determine gear load-carrying capacities at 74°C (165°F); and, the second procedure, described in detail in Appendix 1B of Reference 3, Military Specification MIL-L-27502, was used to determine gear load-carrying capacities at 218°C (425°F).

The ASTM Method D-1947 describes a procedure in which the test oil and support oil temperatures are controlled at 74°C (165°F) and the test gears are allowed to seek their own equilibrium temperature, usually in the range of 75° to 135°C (167° to 275°F) or higher, depending upon the lubricant, gear material, and load applied to the test gears. In the high-temperature gear test procedure described in Reference 3, the test gear temperature is continuously monitored using an infrared radiometer, and is maintained at a constant 218°C (425°F) throughout the test by means of an induction heater.

The general operational procedures for both test methods are very similar and are briefly described as follows: A test rig warm-up period is allowed with all systems functioning with the exception of the drive and the induction heating systems. After the desired test oil and support oil temperatures are attained, the drive system is activated and the speed of the WADD gear machine is increased to 10,000 rpm. If the test calls for a controlled 218°C (425°F) test gear temperature, the induction heating control system is set at the desired temperature, and the test gear temperature is obtained and controlled automatically. The desired load is next set into the load system which automatically loads and controls the load on the gear teeth. After the load is obtained, the interval timer is set for the standard load duration time of 10 min. At the end of the 10-min. period, the timer shuts down the drive system. The operator then turns off the load and the induction heat to the test gears. The machine is then stopped and each tooth on the narrow test gear is visually inspected for scuff. The procedure is then repeated for the next higher load. The test is terminated at least one load step after an average of 22.5 percent scuff is obtained on the narrow gear.

III. TEST LUBRICANTS

Specific details concerning lubricant formulations are not available due to the proprietary interests involved. The following tabulation presents the initial viscosity values, neutralization number data, and the available specification information for the lubricants included in this program:

Lubricant Code	Lubricant Description	Viscosity, cSt 40°C(104°F)	Viscosity, cSt 100°C(212°F)	Neut. No., mg KOH/g
A-1000	MIL-L-23699C	24.23	4.93	0.59
A-1001	MIL-L-27502 Candidate	36.77	6.84	0.11
A-1002	MIL-L-7808H	13.53	3.31	0.05
Y-1009	MIL-L-23699 C.I.[a]	25.66	5.05	0.17

(a) Corrosion inhibited MIL-L-23699 candidate.

IV. RESULTS AND DISCUSSION

A summary of the average gear load-carrying capacities for the various gear material/lubricant combinations included in this program are presented in Table 2 for two temperature levels. In order to expand the usefulness of this gear/lubricant load-carrying capacity program without increasing the program cost, data previously obtained by NAPC and AFAPL at 74°C (165°F) using AMS 6260, Cartech EX 00014, and CBS 1000 M test gears are included in Tables 2 and 3 for comparison purposes. The 74°C (165°F) data for Vasco X-2 ESR test gears and all of the 218°C (425°F) data were obtained by AFLRL in the course of this program. Individual load-carrying capacity determinations for the three high-temperature gear steels are presented in Tables 3 and 4 along with the calculated average, standard deviation, and 95 percent confidence interval for the mean (average) for each test series.

From the 74°C (165°F) data presented in Table 2, it will be noted that an increase in load-carrying capacity was obtained for all three high-hot-hardness gear materials when compared with their equivalent 74°C (165°F) data using AMS 6260 steel gears. The relative ranking of the different gear materials, in the order of increasing load-carrying capacity values for one lubricant, A-1000, is as follows:

Gear Material	Percent of AMS 6260 Value
AMS 6260	100
Vasco X-2 ESR	110
Cartech EX 00014	121
CBS 1000 M	135

It should be pointed out that the increase in load-carrying capacity for the Vasco X-2 ESR steel gears at the 74°C (165°F) test conditions varied from as little as 10 percent for lubricant A-1000 to a maximum of 48 percent for A-1001, based upon their equivalent 74°C (165°F) AMS 6260 gear data.

TABLE 2. SUMMARY OF AVERAGE LOAD-CARRYING CAPACITIES FOR THE VARIOUS LUBRICANT/MATERIAL COMBINATIONS AT TWO TEMPERATURE LEVELS

	Load-Carrying Capacity, N/cm (lb/in.)						
	AMS-6260	Cartech EX 00014		CBS 1000 M		Vasco X-2 ESR	
Lubricant	74°C(165°F)	74°C(165°F)	218°C(425°F)	74°C(165°F)	218°C(425°F)	74°C(165°F)	218°C(425°F)
A-1000	5096(2910) (a)	6151(3512) (a)	3400(1942)	6884(3931) (a)	3976(2270)	5629(3214)	4776(2727)
A-1001	4729(2700) (b)	--	--	--	--	7006(4000)	5376(3070)
A-1002	4378(2500) (c)	--	--	--	--	5716(3264)	3170(1810)
Y-1009	4447(2539) (a)	--	--	--	--	6208(3545)	4956(2830)

(a) Data from NAPC (average of 4 determinations).

(b) Data from AFAPL(average of 6 determinations).

(c) Data from AFAPL(average of 8 determinations).

TABLE 3. LOAD-CARRYING CAPACITY DETERMINATIONS FOR TWO NAVY-SUPPLIED TEST GEAR STEELS AT TWO TEMPERATURE LEVELS

Lubricant	Load-Carrying Capacity, N/cm (lb/in.)			
	Cartech EX 00014		CBS 1000 M	
	74°C(165°F)*	218°C(425°F)	74°C(165°F)*	218°C(425°F)
A-1000	6145(3509)	3545(2024)	7432(4244)	3417(1951)
	6256(3572)	3182(1817)	6778(3870)	3842(2194)
	6102(3484)	3217(1837)	6266(3578)	4261(2433)
	6102(3484)	3657(2088)	7063(4033)	4384(2503)
Average	6151(3512)	3400(1942)	6884(3931)	3976(2270)
Standard Deviation	74(42)	237(135)	490(280)	439(251)
95% Confidence Interval	±72(41)	±231(132)	±480(274)	±431(246)

* Data from NAPC.

TABLE 4. LOAD-CARRYING CAPACITY DETERMINATIONS FOR VASCO X-2 ESR TEST GEARS AT TWO TEMPERATURE LEVELS

Lubricant	Load-Carrying Capacity, N/cm (lb/in.) 74°C(165°F)	218°C(425°F)
A-1000	5345(3052)*	3933(2246)
	6271(3581)	5440(3106)
	5825(3326)	4765(2721)
	5077(2899)	4967(2836)
Average	5629(3214)	4776(2727)
Standard Deviation	528(301)	629(359)
95% Confidence Interval	±516(295)	±616(352)
A-1001	6848(3910)	4545(2595)
	6594(3765)	5970(3409)
	7368(4207)	4476(2556)
	7215(4120)	6511(3718)
Average	7006(4000)	5376(3070)
Standard Deviation	351(200)	1023(584)
95% Confidence Interval	±343(196)	±1002(572)
A-1002	5482(3130)	3499(1998)
	5821(3324)	4042(2308)
	5692(3250)	2151(1228)
	5867(3350)	4096(2339)
		2876(1642)
		2361(1348)
Average	5716(3264)	3170(1810)
Standard Deviation	172(99)	837(478)
95% Confidence Interval	±170(97)	±669(382)
Y-1009	6464(3691)	4200(2398)
	5937(3390)	4881(2787)
	5720(3266)	4629(2643)
	6713(3833)	6571(3752)
		4877(2785)
		4583(2617)
Average	6208(3545)	4956(2830)
Standard Deviation	459(262)	829(473)
95% Confidence Interval	±450(257)	±662(378)

*Individual determination, two determinations obtained per pair of test gears.

Reviewing the 218°C (425°F) data for the three high-hot-hardness gear steels, the relative ranking of the different gear materials, again in the order of increasing load-carrying capacity values for one lubricant, A-1000, is as follows:

Gear Material	Percent of 74°C(165°F) AMS 6260 Value
Cartech EX 00014	67
CBS 1000 M	78
Vasco X-2 ESR	94

Again, it is pointed out that the change in load-carrying capacity values for the Vasco X-2 ESR steel gears at the 218°C (425°F) varied from a loss of 28 percent for lubricant A-1002, to an increase of 14 percent for lubricant A-1001, based upon their respective 74°C (165°F) AMS 6260 gear data.

A plot of the average results and confidence intervals, shown in Table 4, is presented in Figure 1. It will be noted that at the 74°C (165°F) test conditions, lubricant A-1001, the candidate MIL-L-27502, provided the highest load-carrying capacity of the four lubricants evaluated using the Vasco X-2 ESR test gears. A cursory examination of the Vasco X-2 ESR data obtained at the 218°C (425°F) test conditions indicate lubricant A-1001 was also the lubricant having the highest load-carrying capacity at this temperature condition. However, when the 95 percent confidence intervals for the 218°C (425°F) data are considered, no significant differences in the load-carrying capacities for lubricants A-1000, A-1001, and Y-1009 appear to exist at the higher test temperature level using the Vasco X-2 ESR steel test gears. Perhaps one of the most important aspects of this series of tests, although not unexpected, was the apparent large (44.5 percent) loss in load-carrying capacity shown for lubricant A-1002 at the 218°C (425°F) test conditions.

It is apparent from the comparison of load-carrying capacity results at the two test temperature levels that the gear materials included in this

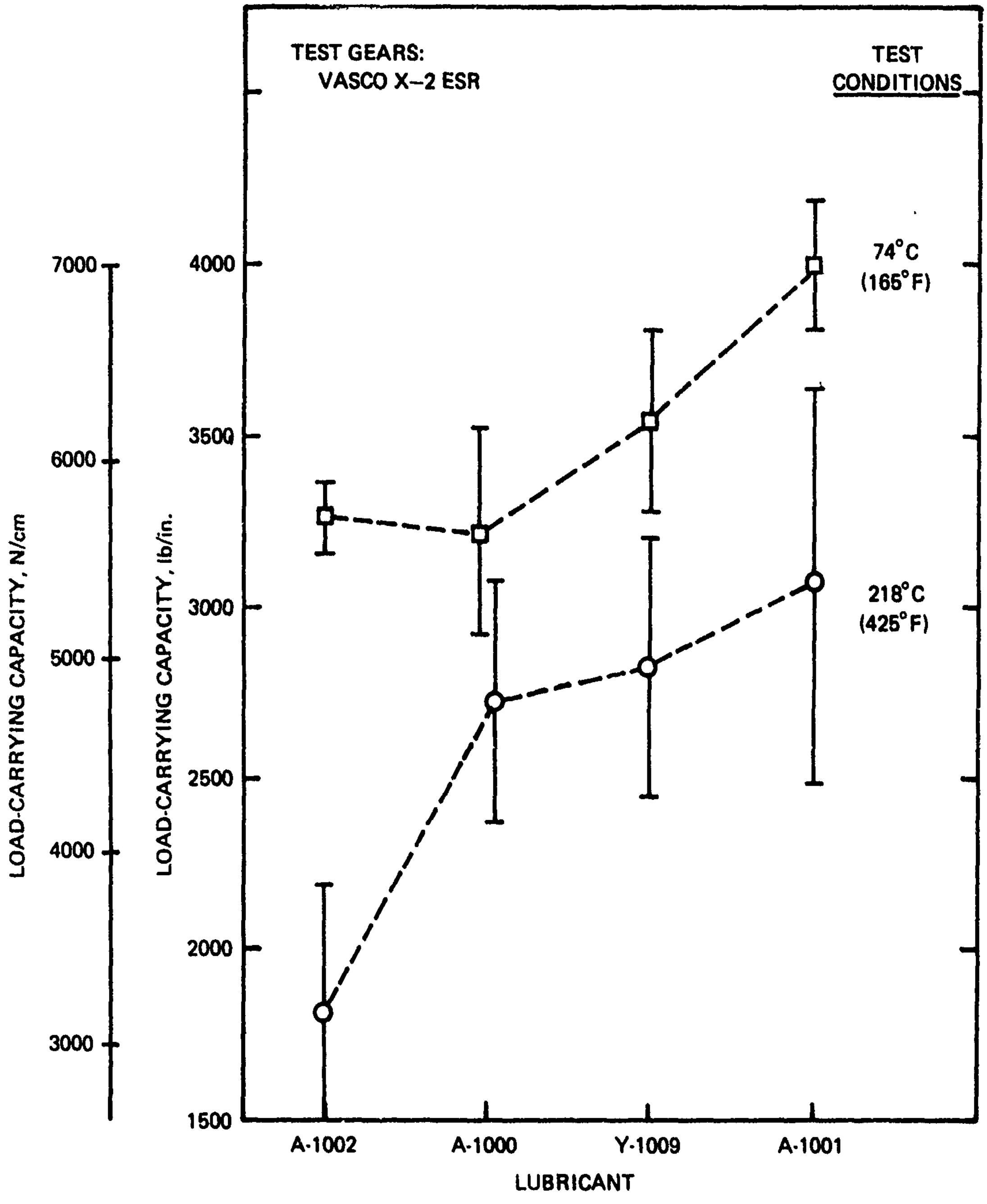

FIGURE 1. LOAD-CARRYING CAPACITY FOR VASCO X-2 ESR TEST GEARS AT TWO TEST TEMPERATURE CONDITIONS

program do not have the same relative ranking at the two temperature levels. This means that load-carrying capacity values obtained at the 74°C (165°F) test condition for one material/lubricant combination cannot be used to accurately predict the load-carrying capacity of that same material/lubricant combination at the higher test temperature condition, 218°C (425°F).

In summary, a comparison of the average load-carrying capacities for the various lubricant/material combinations expressed as a percent of the 74°C (165°F) MIL-L-7808/AMS-6260 load-carrying capacity value is presented in Table 5. Assuming that the load-carrying capacity of a MIL-L-7808 lubricant at 74°C (165°F) using AMS-6260 gears is the minimum acceptable value for satisfactory operation, it is easy to select lubricant/material/temperature combinations which would probably prove satisfactory in service (those having percent values above 100), and those which would probably prove unsatisfactory in service (those having percent values lower than 100).

V. CONCLUSIONS

An increase in gear load-carrying capacity was obtained for the three high-hot-hardness gear materials, Cartech EX 00014, CBS 1000 M, and Vasco X-2 ESR, at 74°C (165°F) test conditions when compared with their equivalent 74°C (165°F) data using AMS 6260-steel gears.

A candidate MIL-L-27502 lubricant, A-1001, provided the highest load-carrying capacity at 74°C (165°F) test conditions of the four lubricants evaluated using the Vasco X-2 ESR test gears.

Although a cursory examination of the data obtained at the 218°C (425°F) test conditions using Vasco X-2 ESR test gears indicated that lubricant A-1001 also provided the highest load-carrying capacity for these conditions, when the 95 percent confidence intervals for these data were considered, no significant differences in the load-carrying capacity for three different lubricants (A-1001, A-1000, and Y-1009) could be determined.

TABLE 5. COMPARISON OF AVERAGE LOAD-CARRYING CAPACITIES FOR THE VARIOUS LUBRICANT/MATERIAL COMBINATIONS EXPRESSED AS A PERCENT OF THE 74°C MIL-L-7808/AMS-6260 VALUE

	Load-Carrying Capacity, %						
	AMS-6260	Cartech EX 00014		CBS 1000 M		Vasco X-2 ESR	
Lubricant	74°C(165°F)	74°C(165°F)	218°C(425°F)	74°C(165°F)	218°C(425°F)	74°C(165°C)	218°C(425°F)
A-1000	116	140	78	157	91	128	109
A-1001	108	--	--	--	--	160	123
A-1002	100	--	--	--	--	130	72
Y-1009	102	--	--	--	--	142	113

Lubricant A-1002, MIL-L-7808H lubricant, suffered a 44.5 percent loss in load-carrying capacity using Vasco X-2 ESR test gears when the test temperature conditions were increased from 74°C (165°F) to 218°C (425°F), while the average loss for the candidate MIL-L-27502, the MIL-L-23699C, and the corrosion-inhibited MIL-L-23699 lubricant was only 19 percent.

From the results presented, it is evident that the load-carrying capacity of gears made from different materials do not necessarily have the same relative ranking when evaluated at two different test temperature levels. Therefore, the load-carrying capacity of one material/lubricant combination at 218°C (425°F) test temperature conditions cannot be accurately predicted from equivalent data obtained at lower test temperature conditions.

VI. RECOMMENDATIONS

Due to the fact that different gear material/lubricant combinations do not necessarily have the same relative ranking at different operating temperature levels, if it is anticipated that a new gear material and/or lubricant is to be subjected to operating temperature conditions significantly above those from which ample satisfactory operating experience is available, it is recommended that comparative test data be obtained at the 74°C (165°F) standard test conditions and the 218°C (425°F) test conditions (or higher test temperature conditions if deemed necessary) in order to evaluate the anticipated degree of success of the new material/lubricant combination.

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